

Tsunami Produced by the Impacts of Small Asteroids

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The fragmentation of a small asteroid in the atmosphere greatly increases its cross section for aerodynamic braking, so ground impact damage (craters, earthquakes, and tsunami) from a stone asteroid is nearly negligible if it is less than 200 meters in diameter. A larger one impacts the ground at nearly its velocity at the top of the atmosphere producing considerable impact damage. The protection offered by Earth's atmosphere is insidious in that smaller, more frequent impactors such as Tunguska only produce air blast damage and leave no long-term scars on the Earth's surface while objects 2.5 times larger than it, which hit every few thousand years, cause coherent destruction over many thousands of kilometers of coast. Smaller impactors give no qualitative warning of the enormous destruction wrought when an asteroid larger than the threshold diameter of 200 meters hits an ocean. A water wave generated by an impactor has a long range because it is two-dimensional, so its height falls off inversely with distance from the impact. When the wave strikes a continental shelf its speed decreases and its height increases to produce tsunami. The average runup in height between a deep water wave and its tsunami is more than an order of magnitude. Tsunami produce most of the damage from asteroids with diameters between 200 meters and 1 km. An impact anywhere in the Atlantic by an asteroid 400 meters in diameter would devastate the coasts on both sides of the ocean by tsunami over 40 meters high. An asteroid 5 km in diameter hitting in mid Atlantic would produce tsunami that would inundate the entire upper East Coast of the United States to the Appalachian Mountains. Studies of ocean sediments may be used to determine when coastal areas have been hit by tsunamis in the past. Tsunami debris has been found to be associated with the Cretaceous - Tertiary impact and should be detectable for smaller impacts.

Introduction

Tsunami may be the most serious consequence of asteroid impacts unless the asteroid is massive enough to produce global, catastrophic changes in the atmosphere, as apparently occurred after the impact responsible for the Cretaceous-Tertiary extinction. Just as on land, much of the kinetic energy of an asteroid that impacts the ocean goes into the formation of a crater, but the crater is not stable. The outward propagation of its rim and its refilling produces a series of waves that propagate outward away from the impact (Gault and Sonett 1982).

In this paper we are primarily concerned with the impacts of small (compared to the depth of the ocean) asteroids that produce waves with amplitudes less than the depth of the ocean. Such deepwater waves do not dampen significantly until they run into shallows where they steepen into breakers and increase in height to form tsunami (Mader 1988). The average tsunami runup, the height of the tsunami in units of the deepwater wave that produced it, is about an order of magnitude.

The height of a deepwater wave only decreases inversely with the distance from its origin, so it can cause serious problems far from the impact. This results from the wave being inherently two-dimensional. The intensity of a three-dimensional disturbance such as an airburst or an earthquake falls off as the inverse square of the distance, so such a disturbance is far more localized than water waves.

There are many anecdotal illustrations of the long-range nature of tsunami; e.g., the earthquake in Chile in 1960 produced deepwater waves that traveled 150 degrees (over 17,000 km) around the Earth to produce tsunami in Japan that were from 1-5 meters high (average about 2 meters) and killed at least 114 people with another 90 people missing (Takahasi 1961). [It is estimated that the full amplitude of the deepwater wave before hitting Japan was 40 cm, so the maximum height above normal sea level was 20 cm, and it had a period of 60 minutes (Iida and Ohita 1961)]. This implies an average tsunami runup of

10 fold and a maximum of 25 fold). In the Hawaiian Islands, at 10,600 km from the epicenter, the maximum runup was 15 meters. The major damage was in Hilo harbor where the maximum tsunami height was over 10 meters and 61 people were killed (Cox 1961). The average tsunami runup in Hawaii is about 40 fold. We shall see that asteroid impacts can produce tsunami vastly larger than the 1960 tsunami and in regions, such as the Atlantic, where coastal areas are poorly prepared for them.

Impacts into Deep Oceans

To determine heights of tsunami produced by an asteroid or comet, we first determine its kinetic energy at its impact with the ocean. Figure 1 (from the work of Hills and Goda 1993) shows the height in the atmosphere at which half the kinetic energy of a stony meteoroid is dissipated. We note that asteroids with radii exceeding 100 meters hit the ground with most of their original kinetic energy. The straight-line portion on the left side of the figure is for asteroids that do not fragment. Fragmentation can enormously increase the effective radius of smaller meteoroids and their rate of energy dissipation in the atmosphere. If we extend the straight line portion of the figure to sea level, we note that if it were not for fragmentation, asteroids with radii larger than 10 meters would be able to penetrate to sea level with most of their kinetic energy. The increased energy-dissipation cross section due to fragmentation causes stony asteroids with radii between 10 and 100 meters to dissipate most of their energy in the atmosphere rather than on impact with the ground.

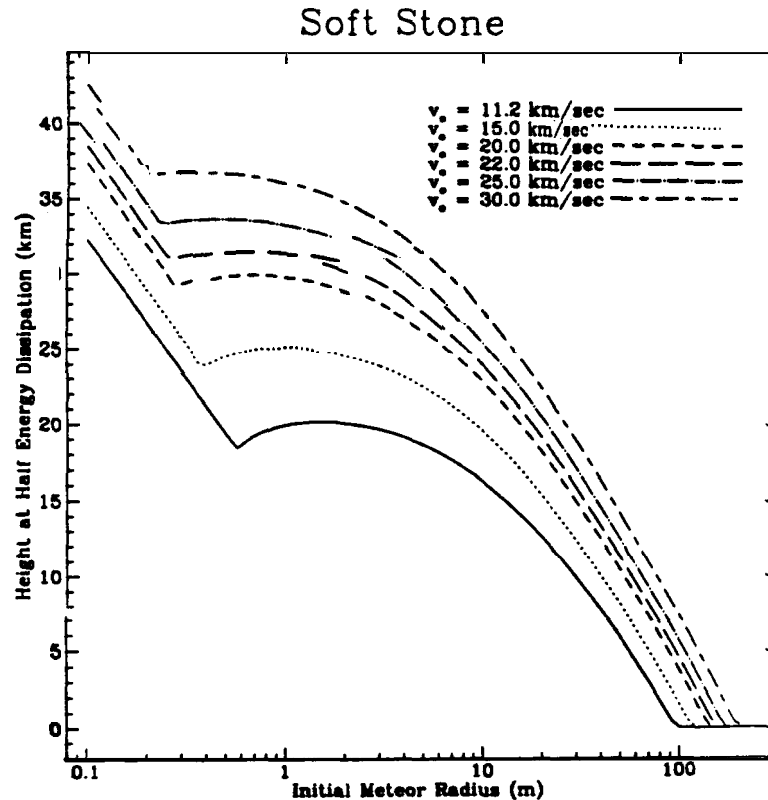


Figure 1. The height (in km) in the atmosphere at which half the initial energy of the impactor has been absorbed. This is for soft (common) stony asteroids. It is given as a function of the radius of the impactor for various impact velocities (in km/s).

We use the impact energy at sea level to find the height of the deepwater wave. An empirical analysis of experiments with underwater nuclear explosives shows that the full height of a deep-water wave at a distance r from the underwater detonation of energy Y is given by

$$h_W = 40,500 \text{ ft} \frac{(Y/\text{kton})^{0.54}}{r/\text{ft}} = 6.5 \text{ meters} \left(\frac{Y}{\text{gigaton}} \right)^{0.54} \left(\frac{1000 \text{ km}}{r} \right) \quad (1)$$

(Glasstone and Dolan 1977). This result is not sensitive to the depth at which the explosion occurs. The height, h , of the water wave above the ocean is half the full height of the wave, so $h = 3.3$ meters at 1000 km from a 1 gigaton $= 4.2 \times 10^{25}$ ergs explosion.

A more recent analysis of Pacific test explosions in deep water with yields between 1 kiloton and 5 megatons and of modeled nuclear explosions of up to 100 megatons, shows a similar equation for the h above the ocean level. One of us (Mader) finds that

$$h = \frac{1}{2} h_W = 4.5 \text{ meters} \left(\frac{Y}{\text{gigaton}} \right)^{1/2} \left(\frac{1000 \text{ km}}{r} \right) \quad (2)$$

The values given by this Equation for $R > 100$ meters are in satisfactory agreement with those given by Equation (1), considering the large extrapolation beyond the experimental points.

Hills and Goda (1993) found the ground impact energies of comets, stony asteroids, and iron asteroids as a function of size and impact velocity taking into account the increase in their aerodynamic cross sections due to fragmentation. Figures 2 and 3 show the full height, H_W , (twice the height h above sea level) of a deep water wave 1000 km from the impact point for nickel-iron and stony meteorites, respectively, as a function of impactor radius for various impact velocities. The heights were gotten by putting the ground impact energies Y found by Hills and Goda (1993) into Equation (1).

We note that the wave heights for stony asteroids less than 100 meters in radius are significantly less than they would be without aerodynamic dissipation. This is also true of iron asteroids with radii less than 40 meters. The smaller cutoff radius for irons is due to their greater strength, which causes them to fragment less easily than stones.

For stones with radii $R > 100$ meters, which suffer no significant energy dissipation in the atmosphere, the deep-water wave height ($h = h_W/2$) above mean sea level at distance r [based on the heights determined by Equation (1)] is given by

$$h = 7.8 \text{ meters} \left[\left(\frac{R}{203 \text{ meters}} \right)^3 \left(\frac{V}{20 \text{ km}} \right)^2 \left(\frac{\rho_M}{3 \text{ g/cm}^3} \right) \right]^{0.54} \left(\frac{1000 \text{ km}}{r} \right) \quad (3)$$

Here a stony asteroid with a radius of 203 meters and a velocity of 20 km/s has an impact energy of 5 gigatons. An asteroid of this size or larger impacts Earth about every 10^4 years.

Asteroids of sufficient size produce craters that exceed the ocean depth. In these cases, Equations (1)-(3) and Figures 2-3 are no longer valid. We shall discuss such impacts in the next section.

Impacts into Shallow Seas

The average ocean depth is 4-5 km. If the depth of the impact crater exceeds the local ocean depth d , we can no longer use Equation (1) to compute the height of the deepwater wave far from impact. It is known from nuclear weapon tests that an explosion in shallow water (e.g., Pacific test Bikini Baker) deposits less mechanical energy into the water than one in deep water (Glasstone and Dolan 1977). Glasstone and Dolan find that the full height of the deepwater wave at distance r from the explosion is given by

$$h_w = 1450 \text{ meters} \left(\frac{d}{r} \right) \left(\frac{Y}{\text{gigatons}} \right)^{0.25} \quad (4)$$

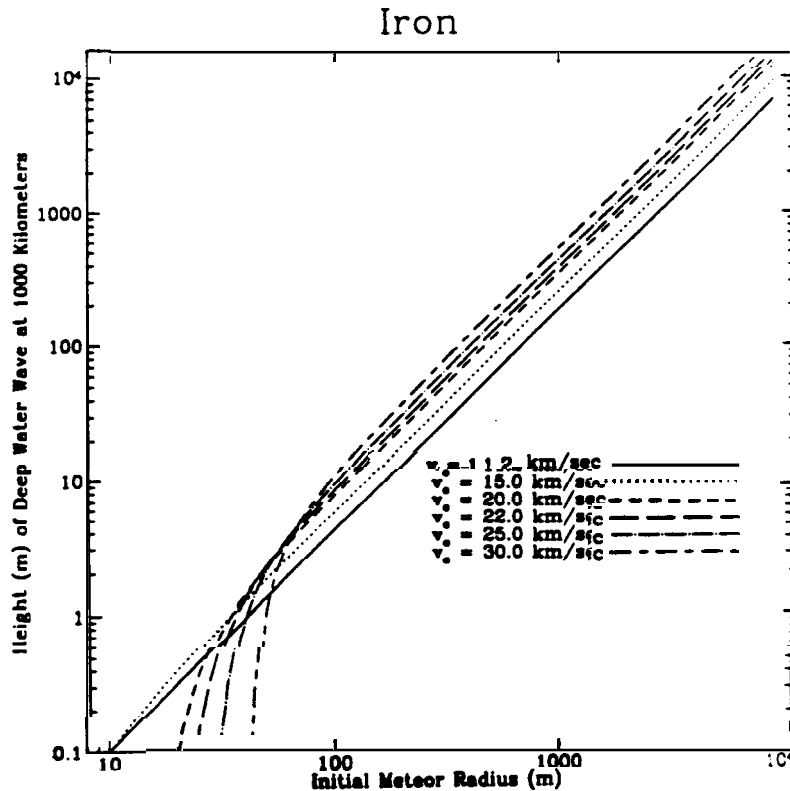


Figure 2. The full height (meters) of a deep-water wave 1000 km from the impact of a nickel-iron asteroid. The height is given as a function of impactor radius for various impact velocities. The height of the wave above mean ocean level is half the full height shown. This wave increases in height by over an order of magnitude to produce tsunamis when it runs into a continental shelf.

where d is the depth of the water and Y is the yield. We note that the wave height increases less rapidly with yield than it does for waves generated in deep water, but there remains an inverse relationship between height and distance from the source. If we let $d = 5$ km, the average depth of the ocean, we find that Equations (1) and (4) give the same full height of $h_w = 8.1$ m at $r = 1000$ km for a yield of $Y = 1.5$ gigaton, which corresponds to a stony asteroid with a diameter of 272 meters and an impact velocity of 20 km/s.

Schmidt and Holsapple (1982) found that the depth of a crater in water is about 12 times the impactor diameter. This suggests that where the impactor diameter significantly exceeds 8% of the depth, it is better to use Equation (4) than Equation (1) to determine the terminal height of the deepwater wave far from the impact. In the ocean, where $d = 5$ km, we should use Equation (4) if the impactor diameter much exceeds 400 meters.

Hydrodynamic simulations by Nemchinov and associates [as given in Hills, et.al. (1994)] of craters produced by asteroids with diameters comparable to the ocean depth suggest that the wave height falls between the values given by Equations (1) and (4), as expected. The fine structure that develops in these hydrodynamic simulations does not allow them to be run to times when the crater has collapsed into a series of outward propagating waves. The calculations must be stopped while the crater is still forming.

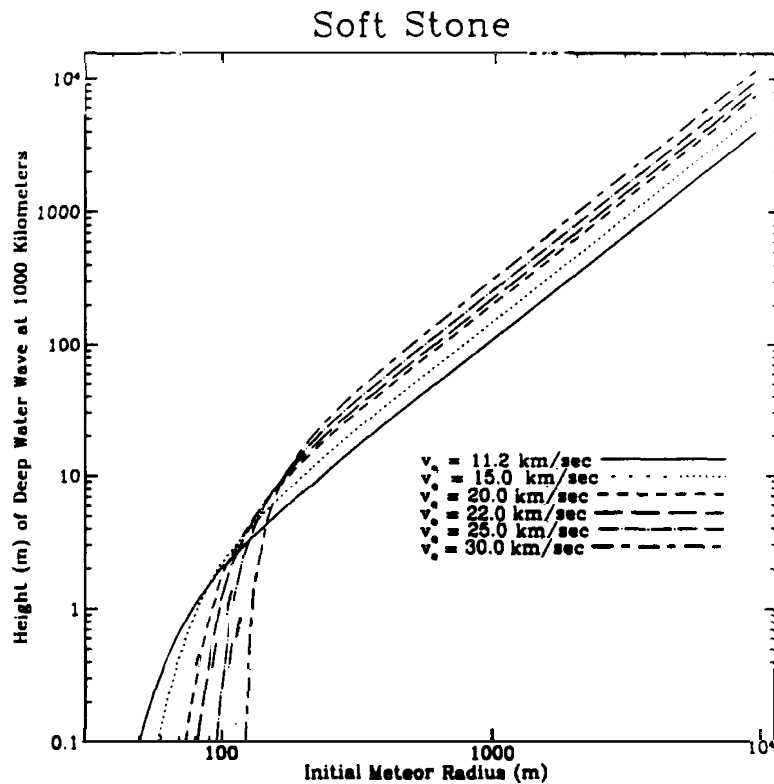


Figure 3. The full height (meters) of a deep-water wave 1000 km from the impact point of a stony asteroid. This height is given as a function of impactor radius for various impact velocities.

From energy considerations, the present authors (Hills and Mader) estimate that the diameter of the water crater when it stops growing is typically about 25 to 30 times that of the asteroid that produced it.

Tsunami

As the deep-water wave goes into a shoal, its speed decreases and its front increases in sharpness and amplitude until it breaks. This wave travels inland from the coast with decreasing speed and height above sea level. We shall first use analytic models to estimate the effect of the tsunami along a typical coast line. We shall emphasize the U.S. East coast. We shall then use a full numerical model to determine the damage from the impact of a large asteroid into the mid Atlantic.

Analytic Model

We noted earlier that the 1960 Chile tsunami produced coastal runups in Japan that averaged 10 fold but reached about 25 fold in the Northern Islands. These values are fairly typical. On Hawaii the average runup is about 40, but it can be less in areas with gradual continental shelves, such as off Florida. As an example, a stony asteroid with a radius of 200 meters (diameter 400 meters) that drops anywhere in the mid Atlantic will produce deep water waves that are at least $h = 4$ meters high when they reach both the European and North American coasts. When it encounters land, this wave steepens into a tsunami with an average height of 40 meters (if it follows the Japanese runups) that hits both sides of the Atlantic nearly simultaneously.

Tsunami Flood Plane. When the tsunami impacts the shore, the maximum distance, X_{max} , to which it surges inland depends on the maximum depth of the water at the shoreline, the runup height h_o , the slope of the shore away from the coast, and the roughness of the ground that the water moves across (cf, Mader 1991). If there is a flat coastal plane on which the flood depth h has a maximum value h_o , the depth at a distance X inland is given by

$$\frac{h}{h_o} = \left[1 + \left(\frac{X}{X_{max}} \right) \right]^{4/3} \quad (5)$$

where the maximum inward distance to which the water flows scales as

$$X_{max} = \frac{h_o^{4/3}}{n^2} A = B h_o^{4/3} \quad (6)$$

where n is the Manning roughness number of the terrain over which the water surges and A is a constant (Bretschneider and Wybro 1977). Here n varies from about 0.015 for very smooth terrain (e.g. mud flats and ice) to 0.070 for very rough coast areas (dense brush and trees and coarse lava formations). Developed areas typically have $n = 0.030$ - 0.035 . For $n = 0.03$ and $h_o = 15$ meters (50 feet), $X_{max} = 2.5$ km (8000 feet) (Bretschneider and Wybro 1977). Putting this scaling factor into Equation (5), we find that

$$X_{max} = 1.4 \text{ km} \left(\frac{h_o}{10 \text{ meters}} \right)^{4/3} \quad (7)$$

We note that in a developed area with a Manning roughness number of $n = 0.03$, a 40-meter tsunami would travel inland about 9 km, a 100-meter one would travel about 30 km, and a 200-meter ones would go 76 km. For croplands or grazing land with a Manning number approaching 0.015, the corresponding figures are 4 times larger. While there may be some difficulties in extrapolating Equation (7) to these large values, it is clear that tsunami of these magnitudes would cause unprecedented damage to low-lying areas in North America such as Long Island.

The damage caused by tsunami results principally from the impact of the debris carried by the moving water. There is much debris in developed areas. This debris acts as a battering ram that effectively scours away the area impacted by the tsunami flood; e.g., in the 1960 Hilo, Hawaii inundation caused by the earthquake in Chile, the steel pipes supporting some of the parking meters in the city were bent to the ground by the ramming of debris carried by the flood. The higher the tsunami flood, the larger its mean flow velocity, and the more effective the ramming.

Because a disproportionate fraction of human resources are close to the coasts, tsunami are probably the most deadly manifestations of asteroid impacts apart from the very large Cretaceous-Tertiary type superkillers.

Numerical Model

While analytic models can approximate the general effect of a tsunami, detailed numerical models are needed to determine the runup and inundation along any particular coast. The height and direction of the deepwater wave along the coast may depend on reflections from nearby land masses as well as on the magnitude, distance, and direction of the impact. The runup depends on the height and direction of the wave and on the topology of the coast.

We did a numerical simulation of a tsunami along the East Coast of the United States produced by an asteroid falling into the mid Atlantic. It was modeled with the 2-dimensional Swan hydrodynamic code with 1-km spatial resolution. Figure 4 shows the position of the impact. We considered an initial perturbation in which the (square) crater was 150 km across with a depth equal to that of the ocean. We estimate that the formation of this crater requires an asteroid about 5 km in diameter, so this impactor is a little larger than the parent object of Comet Shoemaker-Levy 9 that impacted Jupiter in 1994 but an order of magnitude less massive than the impactor responsible for the Cretaceous-Tertiary extinction.

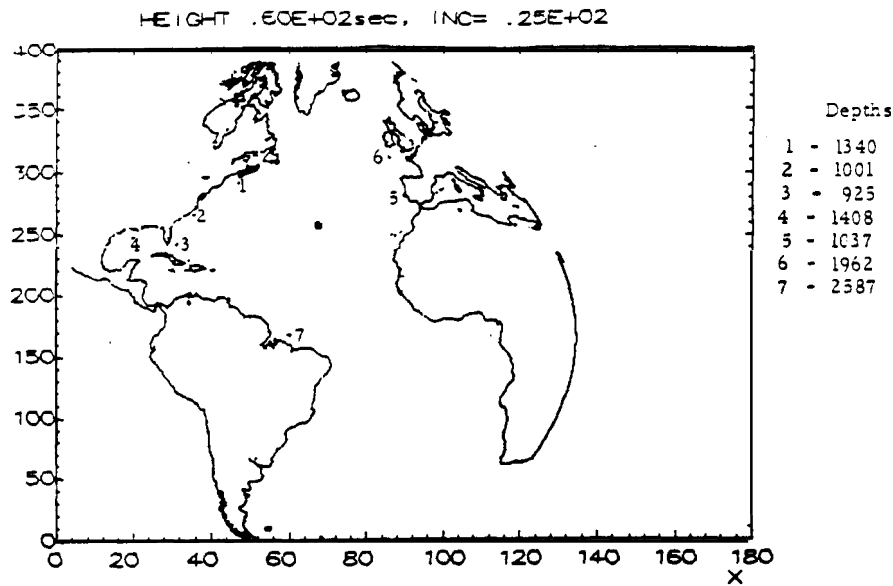


Figure 4. The position in the Atlantic of the 150 km diameter crater produced by an impactor. Also shown are seven locations off the continental shelves at which we determined the heights of the deep water waves in the computer simulation.

Figure 4 shows seven representative locations just outside the continental shelf where the heights of the deepwater wave were determined. The table to the right of the figure shows the depth of the water (in meters) at these points. Table 1 shows characteristics of the series of deepwater waves that passed through each of these seven positions. The second column gives the maximum drop (in meters) in the level of the ocean as the deepwater waves passed by while the next column gives the maximum increase (in meters) in the level of the ocean. We see that off the central East Coast of the United States (Position 2) the maximum wave height and fall off are each 100 meters before the continental runup. Figure 5 shows the height

Table 1. Deepwater wave characteristics from Atlantic impactor.

Location	Min	Max	Period
East Coast (Location 1)	-100	95	1000
East Coast (Location 2)	-100	100	1000
Florida (Location 3)	-95	30	1000
Gulf of Mexico (Location 4)	-5		
Portugal (Location 5)	-85	50	1200
England (Location 6)	-36	100	1500
Brazil (Location 7)	-100	50	1500

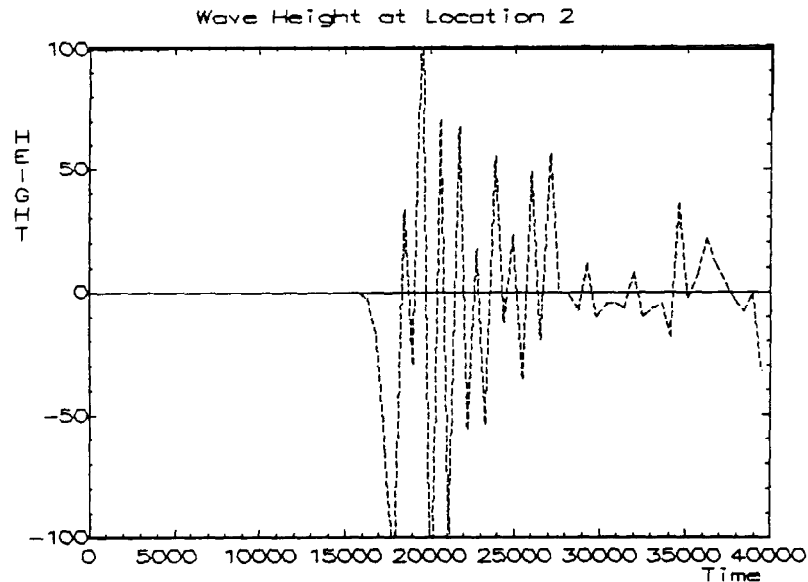


Figure 5. The wave height (meters) as a function of time (seconds) at Location 2 off the East Coast of the United States. This is still in deepwater before any significant tsunami enhancement. We note the large number of separate waves that hit the coast over a period more than 6 hours.

of the wave as a function of time at Location 2. We note the large number of waves that will inundate the shore over a time of over six hours. The final column gives the period of the wave in seconds. These periods are similar to those measured in the 1960 Chilean tsunami. Shorter period deepwater waves disperse without energy dissipation, due to differences in their velocity with period, until their periods lengthen to these values.

The East Coast of the United States is hit very hard by the surge. The wave travels inwards to the foothills of the Appalachian mountains in the upper two-thirds of the United States including surges of more than 200 km across Delaware-Maryland and Virginia. Delaware, Long Island, and all of Maryland below the Piedmont Plateau are completely inundated as are all coastal cities in this area. The damage would be unprecedented in human history.

There are surprises. The Florida coast is largely protected except for the Miami-West Palm Beach area by a gradual continental shelf that reflects most of the tsunami energy back into the Atlantic. Inland areas of Florida are safe despite its low elevation. The enhanced damage in the Miami area compared to rest of Florida points to the particular danger to seaports from tsunami. Seaports are particularly valued if they have a deep offshore channel in otherwise shallow coastal waters. This channel can support a much more energetic tsunami than can the rest of the coast.

The tsunami causes much less damage to Europe than it does to North America because of a large continental shelf off most of the European coast. An exception is the Portugal-Spain peninsula which has almost no continental shelf. The tsunami wraps itself around the peninsula up to the foothills of the mountains. The particular vulnerability of this region may have been forewarned by the tsunami produced by the Lisbon earthquake of two centuries ago. The lost city of Atlantis was allegedly along this section of the Atlantic coast before it was swallowed suddenly by the sea, although there is no archaeological evidence for its existence. Evidence for a strong tsunami along this coast at the same time as one along the upper East Coast of the United States would provide strong support for a major event in the Atlantic of the type expected from an asteroid impact.

Observational Evidence for Tsunami from Impactors

Very large tsunami have occurred. Deposits of unconsolidated corals hundreds of meters above sea level on the Hawaiian Islands of Lanai, Hawaii, Oahu, Molokai, and Maui provide evidence of giant tsunami (Johnson and Kin 1993). On Lanai they are found as high as 326 meters above sea level. A tsunami of similar height occurred in a fiord in Alaska in historical times. These occurrences show that there is no physics limiting large-scale tsunami at least 300 meters high. A tsunami at least 50-100 meters high appeared along the Texas coast after the Cretaceous-Tertiary impact (Bourgeois, et. al. 1989).

Most searches for tsunami in the geological record have been done in the past few years, so it is likely that new evidence for them will appear at an increasingly rapid rate. It may be especially profitable to search for tsunami produced by impacts along the Atlantic coast which is less prone to earthquake-induced tsunami than is the Pacific. Geological (and perhaps archaeological) evidence for large tsunamis along the coasts of the major oceans (due to their large impact cross sections) may be the best counters for impacts of moderately large ($R = 100\text{-}1000\text{ m}$) asteroids.

Conclusions

The atmosphere is ineffective in preventing impact damage to the ground when the diameter of a stony asteroid exceeds 200 meters. For iron meteorites that impact at greater than 20 km/s, the critical diameter is about 40-60 meters. These properties cause a threshold effect whereby stony asteroids less than 200 meters in diameter produce no significant ground (ocean) damage [but those larger than 60 meters in diameter can cause significant damage from airbursts (Hills and Goda 1993)], while those larger than this value can cause catastrophic tsunami.

The growth of the height of the deepwater wave with increasing impact energy slows considerably when the crater depth becomes comparable to the depth of the ocean. This occurs at an impact energy of a few gigatons at a typical ocean depth. The probability is a few times 10^{-4} per year that an asteroid of sufficient size will impact an ocean on the Earth to produce tsunami with average heights exceeding 100 meters along the entire coast of the ocean.

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